Testing the Delft University Pavement Management System

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ABSTRACT

Testing of the Delft University pavement management system on the secondary roadway network of the province of Zuid-Holland in the Netherlands is described. The application of network-level monitoring techniques, riding comfort measurements, skid resistance measurements, and visual condition surveys is discussed. The detailed visual condition surveys have proved to be especially useful. These surveys can be used to predict pavement performance, plan maintenance, and estimate the required maintenance budget levels, as well as determine the present status of the network. Techniques are presented for determining maintenance urgencies and leveling required budgets for a 3-year period. On the project level, the application of falling weight deflection measurements is described. These measurements are used to establish the structural condition of a roadway section. Overlays were designed for a section with a poor structural condition. The average of all individual overlays to be applied appeared to be equivalent to that estimated from the visual condition surveys.

The overall objective of a highway department is to keep its highway network in such a state that both safe traveling of all vehicles is guaranteed and sound structural pavement condition can be maintained without excessive costs. Criteria such as maximum levels of distress or levels of minimum serviceability determine the budget required to achieve this objective. Usually the budget will exceed the total available funds; therefore an approach is required in which an optimum balance between benefits and costs can be found. This approach or management system should incorporate the following components:

1. Procedures to determine visual condition, riding comfort, and skid resistance;
2. Criteria to identify highway sections with poor visual condition, riding comfort, or skid number;
3. Procedures to determine residual lives;
4. Procedures to determine the structural condition in a nondestructive way;
5. Criteria to determine when maintenance should be applied and procedures to determine which maintenance or rehabilitation strategy should be applied; and
6. A methodology to evaluate alternative maintenance options and to select the optimum strategy.

The method developed at the Delft University of Technology incorporates all these components (1). The main objectives of this method or system are to (a) evaluate the pavement condition, (b) estimate the maintenance and rehabilitation needs, (c) determine the budget level for each year in the programming period, and (d) determine budget allocations. These components should be structured in such a way that the total system can be implemented by user agencies with minimal difficulty.

Therefore, before proceeding with any implementation, it is recommended that the workability of the system be tested. In the test program errors and discrepancies can be eliminated and, if needed, adjustments to models and criteria can be applied to improve the management system and make it viable.

In this paper the results of the test program of the Delft University pavement management system (DUPMS) are described. Tests have been executed on (for Dutch circumstances) a relatively large secondary roadway network. In consultation with the Highway Administration of the province of Zuid-Holland, the secondary roadway network of that province was chosen as the testing area (see Figure 1). The network is 380 km long. The subsoil of the province of Zuid-Holland consists mainly of clay or a clay peat combination, except in the coastal region where a sand subsoil is found. Pavement construction varies from a 100-mm asphalt layer on a 350-mm blast furnace slag base layer to a 200-mm asphalt layer on a sand base. The majority of the roads are of the two-lane type, are 2 x 3.50 m wide, and are usually without a paved shoulder. The average daily traffic (ADT) on these roads can range from 4,000 to 20,000, with truck percentages of 15 to 20.

In the test program attempts have been made to find answers to the following issues:

1. Can the system be used on a large network without causing problems in the storage and retrieval of large amounts of data?
2. Can the data inventory, condition surveys, and deflection measurements be conducted within an acceptable time horizon?
3. Are the maintenance and rehabilitation proposals resulting from the survey data and deflection tests acceptable both from a theoretical point of view as well as from practical considerations, or do the various decision criteria have to be adjusted?
4. Does application of the management system lead to optimum budget allocation?

FRAMEWORK OF TEST PROGRAM

Like many currently used pavement management systems, DUPMS makes distinctions between monitoring on the network level and on the project level.

Network-level monitoring involves conducting inventories and several condition surveys to establish the current status of the roadway network. In an efficient system, these activities must be simple because they have to cover the complete network. By introducing criteria such as acceptable levels of serviceability or levels of maximum allowable dis-

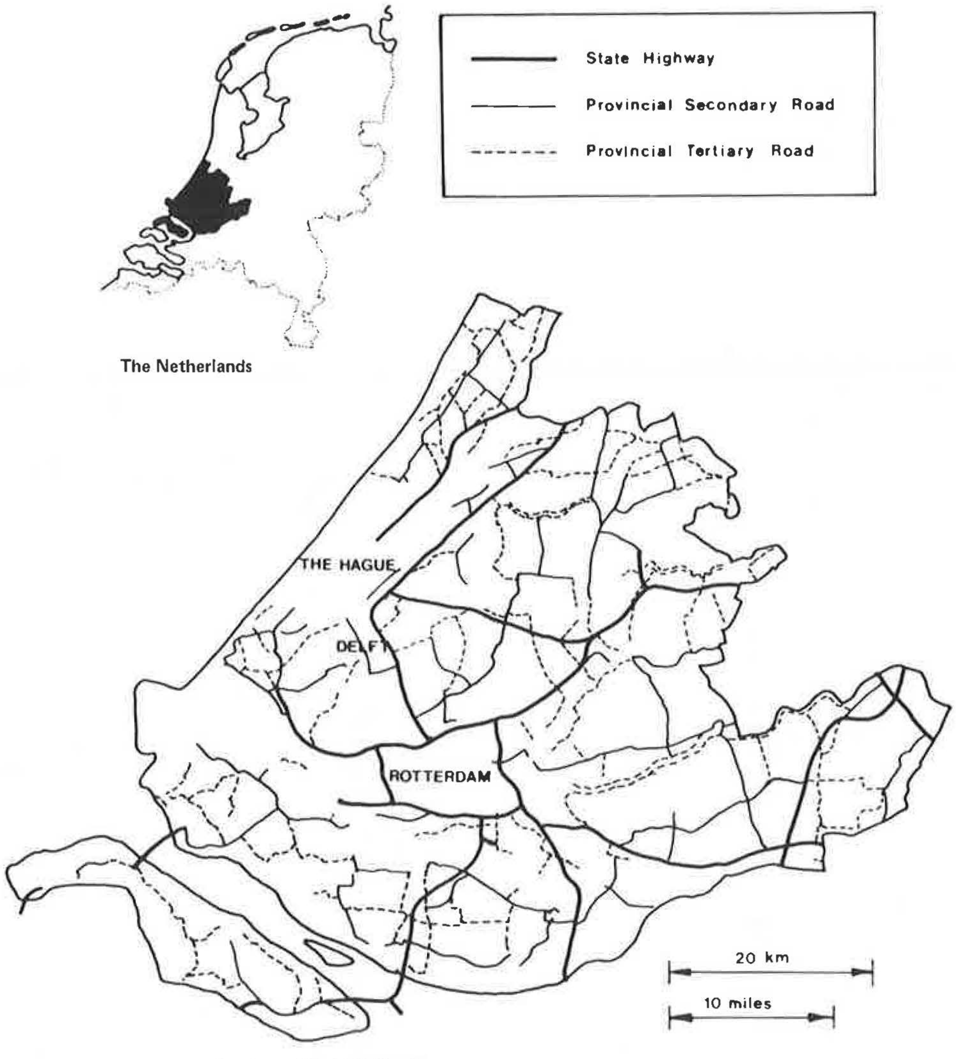


FIGURE 1 Roadway network of province of Zuid-Holland.

tress, an indication of the location and extent of poor road sections in the network can be acquired. Also, a first estimate of maintenance budgets and planning of maintenance activities can be made.

Also, only selected road sections should be selected for project-level monitoring. This restriction is made to save monitoring costs and to speed up the monitoring procedure, because project-level techniques such as deflection testing and high-precision profile measurements are usually expensive and time-consuming. In some cases the interpretation of the survey results requires skilled personnel.

The structure of DUPMS, as tested on the secondary road network of the province of Zuid-Holland, consists of the following elements.

1. Network level
   a. Conduct a data inventory
   b. Determine the visual condition by general visual condition surveys, the objective being to obtain a first ranking of all sections according to their visual condition (based on this ranking a selection is made of roadway sections on which a detailed visual condition survey should be conducted)
   c. Determine the visual condition by detailed surveys to obtain data on the present visual status of the network (the results are used in the interpretation of deflection testings and in the assessment of residual pavement lives)
   d. Determine riding comfort
   e. Determine skid resistance
   f. Select roadway sections for project-level monitoring
   g. Estimate maintenance budget requirements (the results of the detailed visual condition survey can be used for a first estimate of the maintenance and rehabilitation budget needed for the next 3 years)
2. Project level
   a. Determine structural condition by deflection tests
   b. Conduct high-precision profile measurements to evaluate road roughness in a more detailed way (only on sections with poor riding comfort)
   c. Determine the texture depth on all sections with a low skid resistance
   d. Determine overlay design.

One element of DUPMS--the general visual condition survey--has not been executed in the test program. Usually this step, together with the data inventory, is the first step to be executed in the monitoring process. In this case this step has been omitted for the following reason.

Before starting the test program, the various districts of the province of Zuid-Holland, on behalf of the Provincial Highway Administration, had selected all roadway sections to which nonroutine maintenance or rehabilitation should be applied within the next 3-year period. For reasons of time, those selected sections were used in the continuation of the monitoring process because it was thought that the general visual condition survey would yield the same poor sections.

The total length of the selected sections was 110 km, or 250 lane-km, and covered around 30 percent of the secondary road network. A detailed description of the entire test program is presented elsewhere (2,3).

NETWORK-LEVEL MONITORING ACTIVITIES

Data Inventory

In a data inventory, usually data such as age, section boundary geometrics, surface type, and so forth are gathered. A delay in the execution of the monitoring process was caused by invalid, incomplete, and inefficient data storage. Therefore, it is stated emphatically that each district should frame its data bank in such a way that it can provide valid and complete data to a wide range of users.

Riding Comfort

Network-level evaluations of road roughness of the sections tested have been done in terms of riding comfort. These measurements are believed to be suitable for use on the network level because they provide a general impression of road roughness and can be conducted in a simple and fast way.

The Delft University ridemeter (4) was used in the test program. This ridemeter is a compact instrument (25 x 20 x 20 cm) that evaluates comfort based on the comfort criteria proposals of the International Standardization Organization (ISO). Vertical accelerations of the bottom of the car are measured by an external accelerometer and weighted by filters based on the ISO proposals. Subsequently, the average root-mean-square value of the signal is determined over a period of 15 sec, which is equivalent to a 200-m segment when traveling at 48 km/h, or to 333 m when traveling at 80 km/h. In the test program a traveling speed of 48 km/h was used for all sections. The obtained value is displayed on the counter of the ridemeter; it is called the ride index.

A high ride index indicates poor riding comfort. The magnitude of the ride index depends on road roughness, and also on the velocity of the car and car characteristics such as mass, springs, shock absorbers, tire pressure, and so forth.

In the test program only one type of car was used during the testing--a Mercedes Benz 508D with a gross mass of 3570 kg. The car characteristics were assumed to be constant during the 3-day testing period.

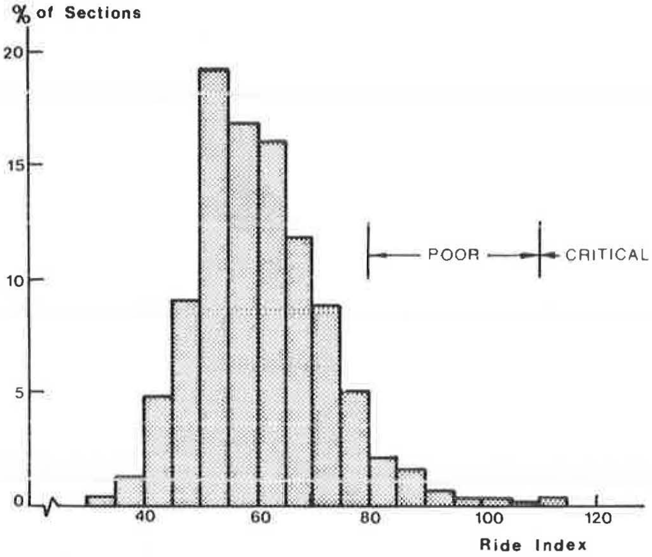


FIGURE 2 Histogram for ride index distribution.

Figure 2 shows a histogram of all ride indices obtained on the Zuid-Holland roadway network. In a previous paper (1) levels of acceptable riding comfort, based on present serviceability index (PSI), have been presented for an Opel Kadett (the U.S. equivalent for this car type is the Chevrolet Chevette). These levels had to be adjusted to fit into the conditions used in the test program. Changes in the car and the level of sensitivity of the ridemeter necessitated multiplication of the levels of acceptable riding comfort by a factor of 4. For this study a ride index of 80 was considered to provide poor riding comfort, whereas at a level of 120 or higher application of maintenance strategies due to lack of riding comfort was considered to be inevitable.

The histogram in Figure 2 shows that only 6 percent of the surveyed sections had poor riding comfort and that only a small number did not meet the minimum level of 120. Consequently, the majority of the network provides fair to good riding comfort. No extra profile measurements were performed on the very poor sections because these sections had poor visual conditions as well. This in turn resulted in deflection testings to determine all feasible maintenance strategies. Because an improvement in the structural condition will result in an improvement in the riding comfort, the expensive profile measurements could be omitted.

Figure 3 shows the relationship between the ride index and the number of deduct points as obtained by the detailed visual condition survey. This figure shows that riding comfort measurements can be used

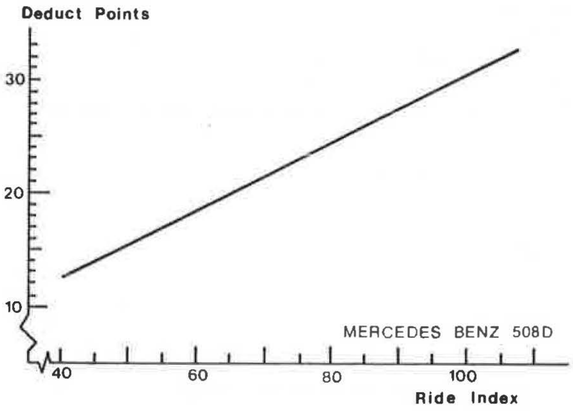


FIGURE 3 Relationship between ride index and deduct points obtained in the detailed visual condition survey.

for the selection and ranking of highway sections in terms of visual condition.

Skid Resistance

An essential requirement of all roads is that vehicles should be able to travel safely. All roadways should therefore have a surfacing with adequate resistance to skidding. In this test program the determination of skid resistance is based on the friction coefficient between the vehicle tire and the pavement surface. The actual tests were performed by the Road Engineering Division of the National Public Works Department. To measure skid resistance they used a trailer with a rolling wheel in an 86 percent slip mode, mounted with a smooth Permanent International Association of Road Congresses (PIARC) tire, towed at a traveling speed of 50 km/h. A wet skid resistance of 0.38 was considered to be the utmost minimum to be permitted on arterial roadway systems, according to proposals of Working Group R1 of the Dutch Study Centre for Road Construction (5). To avoid allowing the surface condition to deteriorate to that level, a warning level was set at 0.45.

No problem occurred in the test program on this condition aspect because a wet skid resistance value of 0.45 or more was measured on all sections. Therefore, because of sufficient resistance to skidding, additional texture depth measurements could be omitted.

Visual Condition

In DUPMS surface distress is monitored by visual condition surveys. The objective of these surveys is to establish the present status of the pavement condition by identifying the type, degree, and extent of distress. By rating these distress identifications and by setting selection criteria, the following characteristics are obtained:

1. Maintenance and rehabilitation volume,
2. Budget level,
3. Additional monitoring actions (e.g., deflection tests), and
4. Location of poor roadway sections.

For reasons of efficiency, extensive visual condition surveys should only be conducted on highway sections where the extent and degree of distress give cause to these detailed surveys. Therefore, a general visual condition survey is recommended as a first action to evaluate the present status of pavement condition in a quick and simple way. Quantity in this phase is more important than quality. Based on the status of the pavement condition, a selection of the sections where detailed surveys should be conducted is made.

General Visual Condition Survey

In DUPMS five general survey distress-type combinations are rated [see Figure 4 (6)]. These ratings express both extent and severity; they range from 1 to 5, where 1 means that no visual distress or only slight distress of limited extent can be observed, and 5 indicates that either moderate distress of large extent or severe distress is present. Usually detailed surveys are recommended when a rating of 3 or higher is assigned to one of the distress types of texture, roughness, or soundness (see Figure 4).

As previously mentioned, this general visual condition survey was omitted in the test program because the Provincial Highway Administration of the test province already provided a list with roadway sections to which some type of nonroutine maintenance should be applied within a 3-year time horizon. It was assumed that the roadway sections from the visual condition survey would be almost similar to that resulting from the general survey.

Detailed Visual Condition Survey

The system developed by Texas A&M University (7) was used for the detailed visual condition survey in DUPMS. Only slight modifications had to be applied to adjust it to Dutch circumstances. In this system the type, extent, and degree of distress can be identified, and each combination is rated according to a deduct point table.

To achieve consistency, the surveys are conducted using distress catalogs with photographs and detailed descriptions of each distress type. This consistency can be enhanced by using sheets on which the exact location and severity of cracks can be drawn (see Figure 5). Introduction of these sheets, along with the standard notation sheets (Figure 6), resulted in a remarkable improvement in consistency of the survey results from each individual survey team (8). An additional benefit of these sheets is that they can be used in the interpretation of the results of deflection tests. These sheets indicate where irregularities in the deflection basin might be explained by the occurrence of cracking.

In the test program 110 km (250 lane-km) was selected by the Provincial Highway Administration. Because of manpower and time constraints, the detailed survey could not be conducted on each section. Instead randomly selected 100-m segments of each section were chosen in such a way that of each section kilometer at least 50 percent was surveyed. It was believed that the difference in deduct points, obtained when each section was surveyed completely, and those obtained in the 50 percent mode, would be neglectable.

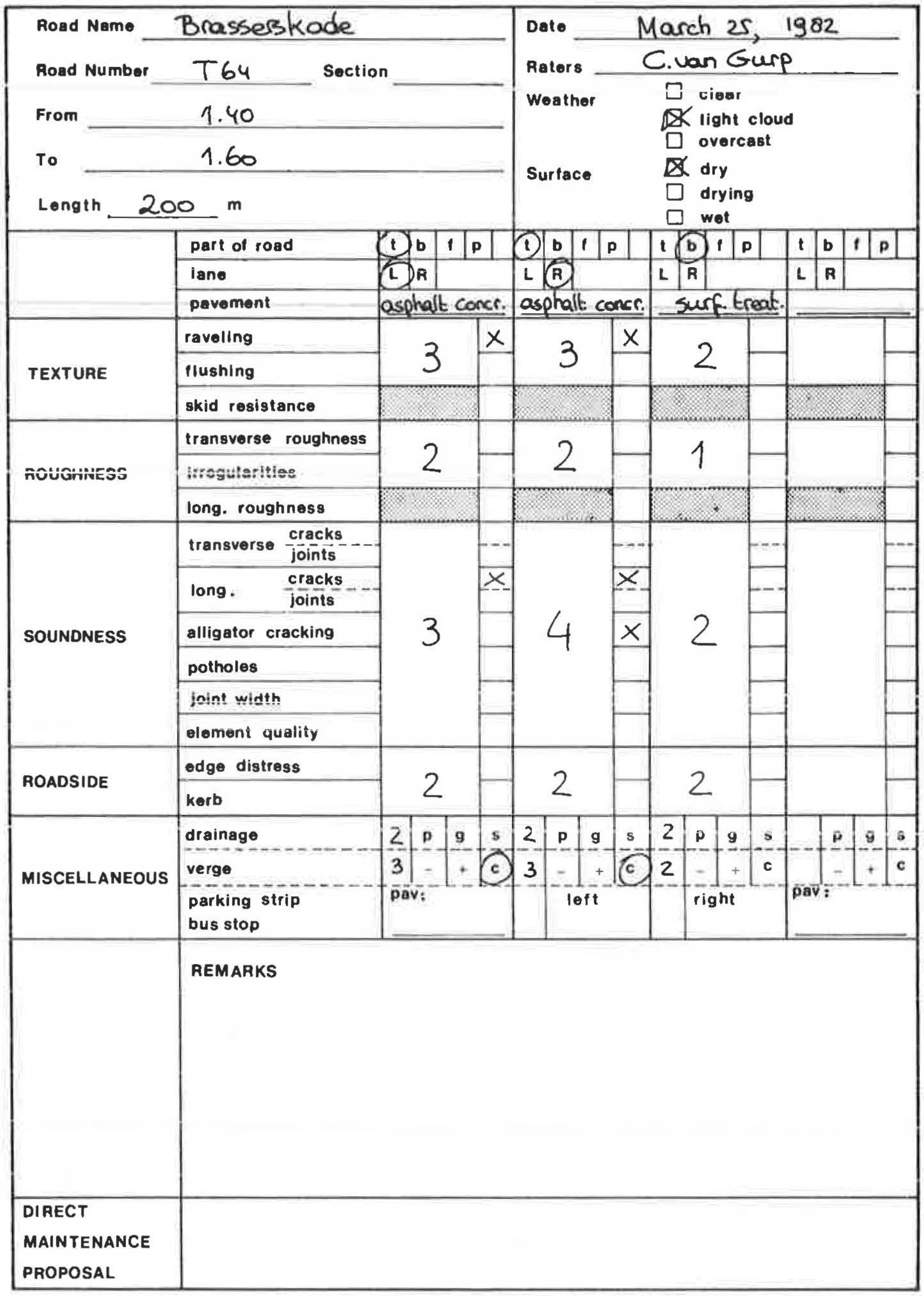
Figure 7 presents a histogram of the deduct points. It shows that only 4.3 percent of the surveyed 100-m segments has more than 40 deduct points. From previous research it is noted that not more than 40 deduct points should be admitted to avoid the risk of excessive damage caused by severe winters (9).

From the conducted surveys it could be concluded that surface defects (e.g., potholes) and rutting are of minor importance. Only a limited number of sections have these distress types. The prevailing distress type is raveling.

All survey data were processed by the computer program WBP-3 (10). This program converts the keypunched survey notations into deduct points and has options to provide graphical displays of deduct point subtotals and to select poor segments. But only the present status of the pavement condition is considered, and no indication of the degree of increase in deduct points is provided. The next section deals with this issue.

Visual Condition Performance

If the present status of a section or a roadway network is unacceptable, maintenance and rehabilitation actions can be programmed to restore the status of the network and to keep it at an acceptable level. Usually these activities have to be planned at least 1 year before actual application. Therefore, besides indications on the present status, data on the de-



Road Name Brasserskade

Road Number T64 **Section** ______

From 1.40

To 1.60

Length 200 m

Date March 25, 1982

Raters C.van Gurp

Weather ☐ clear ☒ light cloud ☐ overcast

Surface ☒ dry ☐ drying ☐ wet

	part of road	[✓ t] b f p		[✓ t] b f p		t [✓ b] f p		t b f p	
	lane	[✓ L] R		L [✓ R]		L R		L R	
	pavement	asphalt concr.		asphalt concr.		surf. treat.			
TEXTURE	raveling	3	X	3	X	2			
	flushing								
	skid resistance	▨		▨		▨		▨	
ROUGHNESS	transverse roughness	2		2		1			
	irregularities								
	long. roughness	▨		▨		▨		▨	
SOUNDNESS	transverse cracks	3		4		2			
	transverse joints								
	long. cracks		X		X				
	long. joints								
	alligator cracking				X				
	potholes								
	joint width								
	element quality								
ROADSIDE	edge distress	2		2		2			
	kerb								
MISCELLANEOUS	drainage	2 p g	s	2 p g	s	2 p g	s	p g	s
	verge	3 – +	[✓ c]	3 – +	[✓ c]	2 – +	c	– +	c
	parking strip bus stop	pav:		left		right		pav:	

REMARKS

DIRECT MAINTENANCE PROPOSAL

FIGURE 4 General visual condition survey sheet *(6)*.

gree of deterioration of the roadway network cannot be omitted in a pavement management system. This degree of deterioration in DUPMS is assessed by visual condition performance models. Periodic surveys provide the data for these models. Policy variables such as levels of maximum acceptable number of deduct points decide when a roadway section will enter the less-acceptable condition phase. The actual date of transition into this lower phase is a useful tool in planning maintenance activities and estimating maintenance costs. A short abstract of the model is presented in the following paragraphs. A complete description is provided elsewhere (11,12).

Visual Condition Performance Models

To compare distress types or combinations of distress with each other, the visual condition index has been introduced. This index links the current number of deduct points to its corresponding maximum:

$$P_v = 1 - (dp/dp_{max}) \qquad (1)$$

where

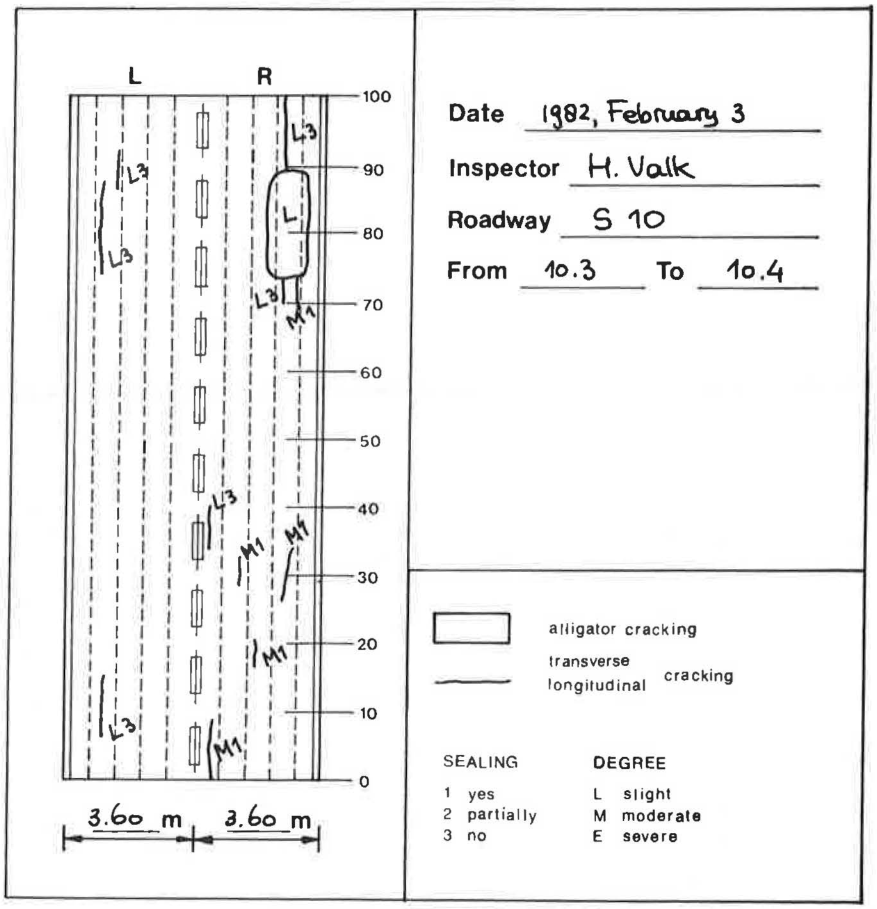
P_v = visual condition index,
dp = number of deduct points, and
dp_{max} = maximum number of deduct points.

From periodic surveys, the decline of P_v with time could be derived:

$$P_v = 1 - \exp\{\alpha[(t/T) - 1]\} \qquad (2)$$

where

t = years since construction,



Date 1982, February 3

Inspector H. Valk

Roadway S 10

From 10.3 To 10.4

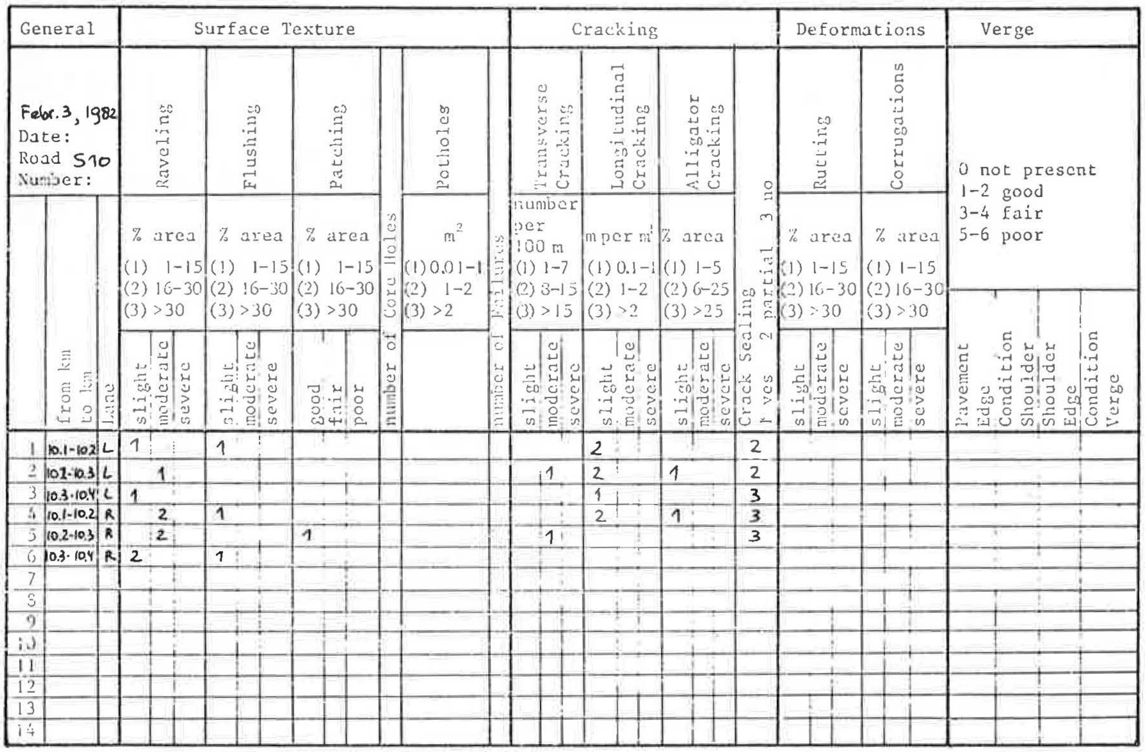
▭ alligator cracking

— transverse / longitudinal cracking

SEALING
1 yes
2 partially
3 no

DEGREE
L slight
M moderate
E severe

FIGURE 5 Cracking notation sheet.



General			Surface Texture												Cracking										Deformations						Verge			
Febr. 3, 1982 Date: Road S10 Number:			Raveling			Flushing			Patching			number of Core Holes	Potholes	number of Failures	Transverse Cracking			Longitudinal Cracking			Alligator Cracking			Crack Sealing 1 yes 2 partial 3 no	Rutting			Corrugations			0 not present 1-2 good 3-4 fair 5-6 poor			
			% area (1) 1-15 (2) 16-30 (3) >30			% area (1) 1-15 (2) 16-30 (3) >30			% area (1) 1-15 (2) 16-30 (3) >30				m^2 (1) 0.01-1 (2) 1-2 (3) >2		number per 100 m (1) 1-7 (2) 8-15 (3) >15			m per m^2 (1) 0.1-1 (2) 1-2 (3) >2			% area (1) 1-5 (2) 6-25 (3) >25				% area (1) 1-15 (2) 16-30 (3) >30			% area (1) 1-15 (2) 16-30 (3) >30						
	from km to km	Lane	slight	moderate	severe	slight	moderate	severe	good	fair	poor				slight	moderate	severe	slight	moderate	severe	slight	moderate	severe		slight	moderate	severe	slight	moderate	severe	Pavement Edge Condition	Shoulder	Shoulder Edge Condition	Verge
1	10.1-10.2	L	1			1												2						2										
2	10.2-10.3	L		1												1		2			1			2										
3	10.3-10.4	L	1															1						3										
4	10.1-10.2	R		2		1												2			1			3										
5	10.2-10.3	R		2					1							1								3										
6	10.3-10.4	R	2			1																												
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FIGURE 6 Detailed visual condition survey sheet.

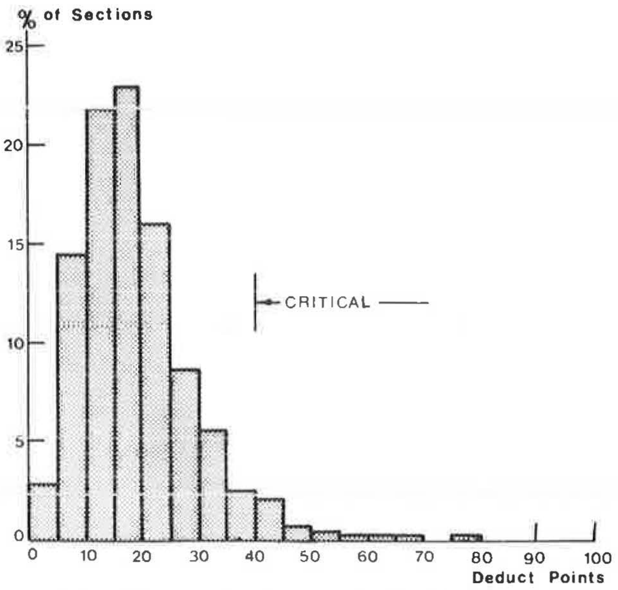


FIGURE 7 Histogram for deduct point distribution.

T = pavement life (P_V = 0), and
α = construction parameter.

Figure 8 shows the performance curve of the visual condition index. In this graph the ratio t/T is called the life index. The magnitude of the construction parameter (α) determined the shape of the performance curve. A high α value involves a steep decline of the visual condition index when the pavement life expires, whereas a low α value causes a more gradual, predictable deterioration. Usually asphalt pavements with rigid bases have high α values (α = 7 to 8), whereas constructions with unbound bases have low α values (α = 3 to 4).

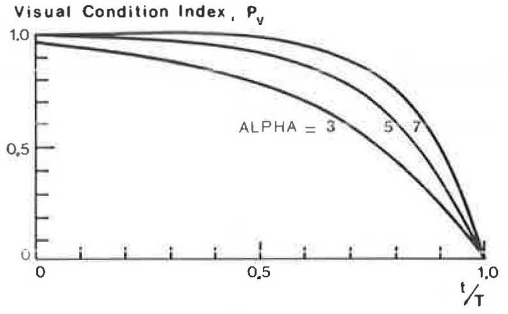


FIGURE 8 Visual condition performance curves.

By periodic surveying, P_V - t combinations enable the determination of α and T by using linear-regression techniques. For a first survey, the construction parameter (α) can be assessed by using the data in Table 1 to determine T. When more survey data are available, a more appropriate α value can be determined.

Condition Phase and Minimum Level

If P_V = 0, the maximum number of deduct points has been assigned and consequently the roadway section involved has reached its pavement life for the distress type considered. When P_V = 0, the section has failed already, and reconstruction is inevitable. To avoid large expenditures and to provide an acceptable level of serviceability, the visual condition index should not drop to its bottom value.

TABLE 1 Construction Dependency of α Value

Distress Type	Raveling	Cracking	Overall Condition
Construction type			
Asphalt layers on cement-bound base	5	7.6	7.4
Asphalt layers on base of blast furnace slags showing cementation	5	5–8.5	6–8.7
Asphalt layers on unbound base	5	3–3.5	4.3
Bituminous construction	5	5.5	5.5

Maintenance should be applied when the degree of deterioration is only limited. Figure 9 shows the process of deterioration for a number of roadway sections. It can be seen that the lower the minimum acceptable level chosen, the more deferral in maintenance will be accepted. From data of highway authorities it appears that maintenance activities should be started when the visual condition index has dropped to 0.7 for cracking and 0.6 for the overall condition. Figure 9 shows that not every roadway section has the same degree of deterioration. It was thought necessary to take this degree into account. This has been done by the maintenance urgency range; that is, the period required for the visual condition index to drop from its minimum level to its ultimate minimum level. This level is set to 0.5 for cracking and 0.4 for the overall condition. The shorter the urgency, the less maintenance can be deferred.

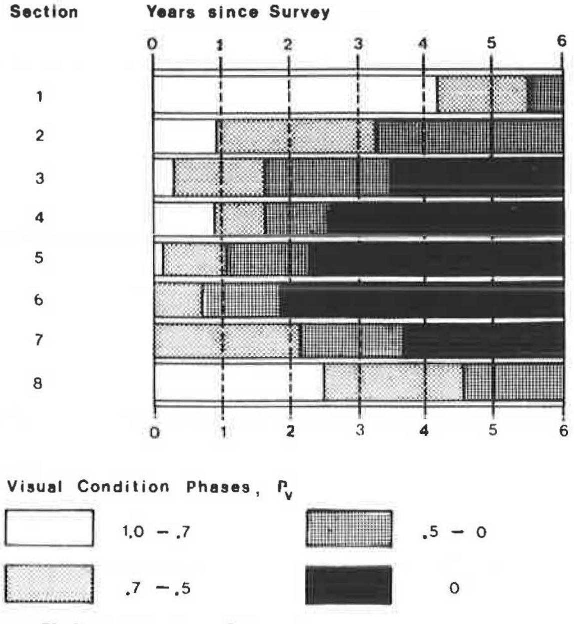


FIGURE 9 Visual condition phases.

Confidence Levels

The procedure previously described can be run for each 100-m survey segment. In the test program, however, only roadway sections selected by the districts were used. For each of these sections, the mean and standard deviation of the number of deduct points of the corresponding survey segments were calculated. The mean and standard deviation of the visual condition index could be derived from these data.

When this mean visual condition index is entered in the performance model, a mean life index and mean condition phase lives will be obtained. A mean value indicates that there is the probability that 50 percent of the section will have a lower visual condition index, and subsequently a shorter pavement life. This probability can be diminished by entering a lower visual condition index. If the combined mean minus standard deviation is entered, the probability that parts of the roadway section will have a shorter pavement life has already been reduced to 15 percent. Figure 10 shows the influence of the choice of confidence level on the condition phase length of Section 1 from Figure 9.

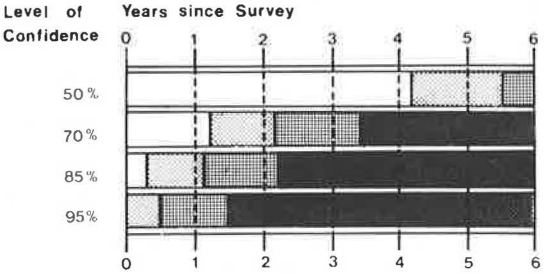


FIGURE 10 Relationship between level of confidence and visual condition phases.

Based on confidence levels, condition phases, and minimum levels, plans for maintenance activities, maintenance costs, and reinspection and deflection tests are made. For determining visual condition indices, residual lives, and condition phases, the computer program PLAIN has been developed (12).

Estimating Volume and Costs of Maintenance

In the previous section it was noted that, based on levels of the minimum acceptable visual condition index, roadway sections with high maintenance urgency can be selected. By using the visual performance models, a ranking of those sections can be made according to their maintenance urgency, which in turn can be used in planning maintenance and rehabilitation and in estimating maintenance costs. Although the total surface area to be improved is known and the data on pavement condition in terms of deduct points or visual condition index are gathered, no exact programming of maintenance or an exact allocation of funds to individual projects can be made. The network-level data are not accurate enough and do not yield information on the structural condition that is detailed enough. Therefore deflection measurements are recommended. But for a general indication of the budget required, visual condition survey results are satisfactory.

Estimating Maintenance Volume

An overlay design is usually based on the present structural condition, the structural condition at the end of the design period, and the length of the design period. The sections on Structural Condition and Overlays (presented later in this paper) will deal with this issue in more detail. They also will demonstrate how the structural condition index can be assessed from the visual condition index. This means that, based on data from visual condition surveys, an indication of the overlay required can be obtained. This overlay design will of course be rough because the conversion from the visual condition index to the structural condition index will be subjected to inaccuracies. But based on this rough overlay design, an estimate of maintenance volume and maintenance costs can be made. Evaluation of the overlay designs based on deflection measurements indicated that the visual condition data yielded an overestimated overlay thickness in some cases, whereas in other cases the overlay thickness was underestimated. However, the average overlay thickness derived from visual condition survey data overestimated the average overlay thickness, as determined by using deflection test data, by only 4 percent. Therefore this method can be used on the network level to indicate the maintenance volume and corresponding costs. For an exact allocation of funds, more accurate and detailed data are needed.

This method of determining the maintenance volume on the network level was used in the Zuid-Holland test program. A study was made of how the distribution of the total surface area of the surveyed sections to be maintained would change with changing minimum acceptable visual condition index levels and levels of confidence.

A previous section indicated what should be the minimum acceptable level and what should be the ultimate minimum level for the visual condition. Between these values, the minimum allowable visual condition indices have been varied to test the maintenance volume dependency. Three levels have been used:

1. Level A: Minimum visual condition index for cracking = 0.7, and minimum visual condition index for overall condition = 0.6;
2. Level B: Level A - 0.1; and
3. Level C: Level A - 0.2.

The determination of the maintenance volume has been performed for four levels of confidence (i.e., 50, 70, 85, and 95 percent). Figure 11 shows the relationship between the maintenance volume (expressed in surface area of the surveyed sections) and the minimum acceptable levels and confidence levels. This figure shows that there is a shift in surface area to be maintained to the first year, when a high minimum level of acceptable visual condition and a high level of confidence are chosen. This peak diminishes when one or both on these levels are lowered. Over a 3- to 4-year period the maintenance volume is less dependent on these levels. Therefore, for reasons of saving on maintenance volume, there is no need to let the pavement deteriorate to a low acceptable level.

Estimating Maintenance Costs

Deferral of maintenance leads to an increase in the maintenance budget. If the visual condition index has dropped to zero, the construction will be in such a poor state that only expensive rehabilitation can restore the pavement condition to an acceptable level. Deterioration of the condition involves crack propagation through the construction. At a visual condition index of $P_V = 0$, cracking has propagated through the entire construction, whereas at a level of $P_V = 0.7$, cracking has only propagated for 60 percent. Based on this and other results of crack growth analyses (13), it could be calculated that dropping the minimum allowable visual condition index for cracking from 0.7 to 0.6 or 0.5 will involve an overlay thickness of 1.3; that is, 1.75

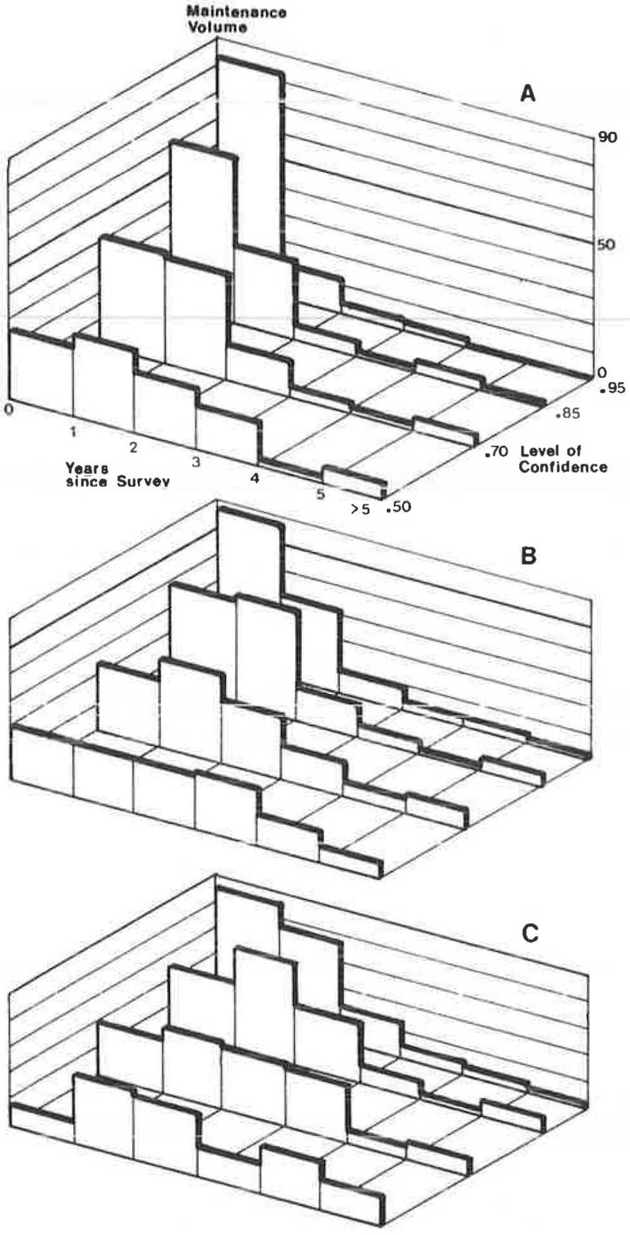


FIGURE 11 Histogram for maintenance volume distribution for three minimum levels for the visual condition index.

TABLE 2 Additional Maintenance Cost Indices

Level of Confidence (%)	Variation Coefficient of Visual Condition by Level of Minimum Acceptance Visual Condition[a]								
	0.1			0.2			0.3		
	A	B	C	A	B	C	A	B	C
50	1.02	1.19	1.53	1.11	1.29	1.58	1.22	1.34	1.59
70	1.02	1.10	1.39	1.04	1.14	1.36	1.09	1.20	1.36
85	1.00	1.05	1.27	1.02	1.06	1.20	1.04	1.09	1.20
95	1.00	1.02	1.15	1.00	1.02	1.07	1.01	1.03	1.07

[a] Level A: minimum visual condition index for cracking = 0.7, and minimum visual condition index for overall condition = 0.6; Level B: Level A – 0.1; and Level C: Level A – 0.2.

thicker than would be needed if the overlay was applied when P_V was 0.7. These factors are directives and are based on crack growth characteristics of common Dutch asphalt mixes.

In estimating the budget required, the magnitude of the variation in the visual condition index of the occurring distress is of importance. If this variation is large, then for any level of confidence there will be more sections with a poor index than in the case of a small variation. This indicates that, in the case of a large variation, each unit of surface area to be maintained requires more budget than would be needed for this same area in the case of a small variation. The data in Table 2 give the magnitude of this effect as a function of level of confidence, minimum acceptable visual condition index, and coefficient of variation in the visual condition. Figure 11 shows that in year 1, for Level A and a confidence level of 85 percent, 61.0 percent of the surveyed area will need maintenance, whereas for Level C 24.7 percent will need maintenance. When a variation in condition within the sections of 0.2 is assumed, then in the first case 61.0 x 1.02 = 61.2 unit costs and in the second case 24.7 x 1.20 = 29.6 unit costs are required.

Figure 12 shows the result of application of the data in Table 2 to Figure 11. Table 2 unit costs have been calculated for a variation coefficient of 0.2 and are corrected for inflation and rates of discount. The chosen rate of inflation is 6 percent and the rate of discount is 10 percent. The data in Table 3 give the cumulative unit costs over a 4-year period. An estimate of the actual maintenance costs can be made based on these costs.

Planning Maintenance

The data in Table 3 indicate that for the combination P = 70 percent, Level A is the combination with the lowest costs. However, 85 percent of the maintenance budget is concentrated in the first 2 years of the 4-year analysis period. For the combination P = 70 percent, Level B indicates that for an additional 2.6 percent, a more equilized distribution of the budget required will be obtained.

If no acceptable distribution can be found, the distribution can be adjusted by shifting maintenance projects forward or backward in time. The choice of which project or section should be shifted can be based on the visual performance of the project or section considered. Figure 9 shows the degree of deterioration of a number of sections. Sections 2 and 4 in this figure will enter the condition phase 0.7 - 0.5 at the same date. Section 4, however, will complete this phase more quickly and should have a higher maintenance urgency than Section 2. Therefore, if one of these sections should be dropped from the maintenance program temporarily, it would be preferable to select Section 2.

PROJECT-LEVEL MONITORING ACTIVITIES

In the previous sections of this paper all network-level monitoring activities, as performed in the test program, have been described. By introducing decision criteria, the surveyed sections can be categorized, maintenance can be planned, and the necessary project-level monitoring activities can be selected.

As already mentioned in the sections on Riding Comfort and Skid Resistance, there was no need to evaluate roughness and skid resistance in a more detailed way. The number of sections with insufficient riding comfort or skid resistance was so small that only attention will be paid to the diagnostic survey of the structural condition.

It was also noted that prediction models of pavement performance in terms of visual condition

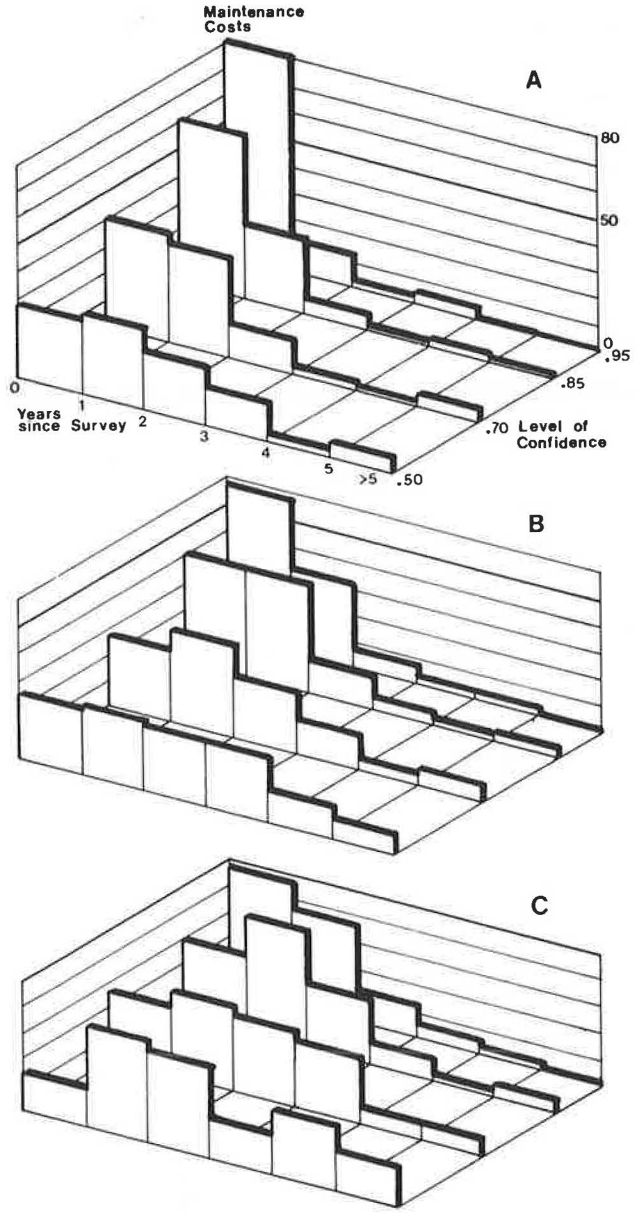


FIGURE 12 Histogram for maintenance costs distribution for three minimum levels of the visual condition index.

can be useful in determining residual lives, condition phases, and maintenance volume. The visual condition performance model can also indicate the structural condition, but to acquire more detailed information deflection tests should be taken. These tests should only be taken if the results of the visual condition survey give cause to these activities. It would take too much time, personnel, and cost if each section was monitored in this way. How these sections were selected is presented in the next sections.

TABLE 3 Maintenance Unit Costs Over a 4-Year Period

	Level of Minimum Acceptable Visual Condition[a]		
Level of Confidence (%)	A	B	C
50	94.5	96.4	100.6
70	91.7	94.1	110.3
85	92.9	94.1	103.7
95	94.8	93.8	96.4

Note: Data are for the Zuid-Holland secondary road network, 1982.

[a] Level A: minimum visual condition index for cracking = 0.7, and minimum visual condition index for overall condition = 0.6; Level B: Level A – 0.1; and Level C: Level A – 0.2.

Distinction is made between indicative falling weight deflection measurements (one data point every 100 m) and diagnostic falling weight deflection measurements (five data points every 100 m).

Indicative Deflection Measurements

Indicative deflection measurements were thought to be necessary if the visual condition index for cracking in asphalt constructions with rigid bases dropped below 0.8. These pavement structures can show a steep increase in the extent of cracking when the pavement life expires. Therefore these indicative measurements leave a larger margin in terms of time to plan maintenance strategies. Indicative measurements should also be taken if no more than 3 years have passed since construction, while the visual condition index for cracking has already dropped below 0.8. If such new construction already shows that extent of distress, the structural condition should be monitored periodically to take precautions to avoid rapid deterioration.

Diagnostic Deflection Measurements

In general, diagnostic deflection measurements should be taken if the visual condition index for cracking is 0.7 or lower. In this case the structural condition has deteriorated to such a degree that detailed information to determine feasible maintenance strategies is required.

Sometimes cracking will not be the prevailing distress type. In this case diagnostic measurements are recommended if the visual condition index for the overall condition drops below 0.7. No measurements are required if the visual condition index for cracking is still 0.8 or more. If the visual condition index for cracking is 0.8 or lower and the residual life is less than 2 years for constructions older than 3 years, diagnostic measurements must be taken to determine the most feasible strategy.

Structural Condition

In DUPMS monitoring the structural condition on the project level is done by falling weight deflection measurements. The objective of these tests is to obtain detailed information on the load-carrying capacity and the degree of deterioration. The load-carrying capacity is characterized by the equivalent layer thickness calculated to Odemark's theory (14):

$$he = 0.9 \sum_{i=1}^{n-1} h_i \sqrt[3]{E_i/E_n} \qquad (3)$$

where

he = equivalent layer thickness,
h_i = thickness of layer i,
E_i = stiffness of layer i,
E_n = stiffness of layer n = subgrade modulus, and
n = number of layers.

By using this relationship, which was derived between the equivalent layer thickness and the deflection basin, the equivalent layer thickness can be estimated from deflection measurements. Because loading magnitude and temperature influence the deflections and consequently the equivalent layer thickness, adjustments have to be applied to correct for these factors. Besides these factors there is a dependency of the equivalent layer thickness on the subgrade modulus. In order to compare different constructions with each other, adjustments are applied in such a way that two identical equivalent layer thicknesses will relate to identical performances (1,13).

A maximum value of the equivalent layer thickness is determined at the moment of construction. A minimum value of the pavement condition is considered where a crack has propagated through all bound pavement layers and where no transfer of the load caused by aggregate interlock across the crack takes place. This condition of a fully developed crack coincides with a visual condition index of $P_v = 0$.

The degree of structural deterioration of a pavement structure is represented by the structural condition index:

$$P_d = he_n/he_o \qquad (4)$$

where

P_d = structural condition index,
he_n = equivalent layer thickness after n load applications, and
he_o = initial equivalent layer thickness.

Figure 13 shows the decrease of the structural condition index as a function of the number of load applications and the dispersion in the layer thicknesses and layer moduli (= $S_{\log N}$). This $S_{\log N}$ value can be determined by deflection measurements (13). With use of the previously mentioned definition of the minimum equivalent layer thickness, calculations indicated that this minimum corresponds to a minimum P_d = 0.65 if the surface curvature index is smaller than 140 μm, and 0.75 if the surface curvature index is greater than 200 μm. For intermediate curvature indices, intermediate minimum structural condition indices can be used (13). This minimum index, and the corresponding number of load applications, is called N.

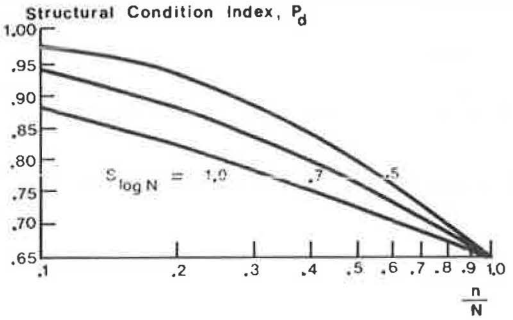
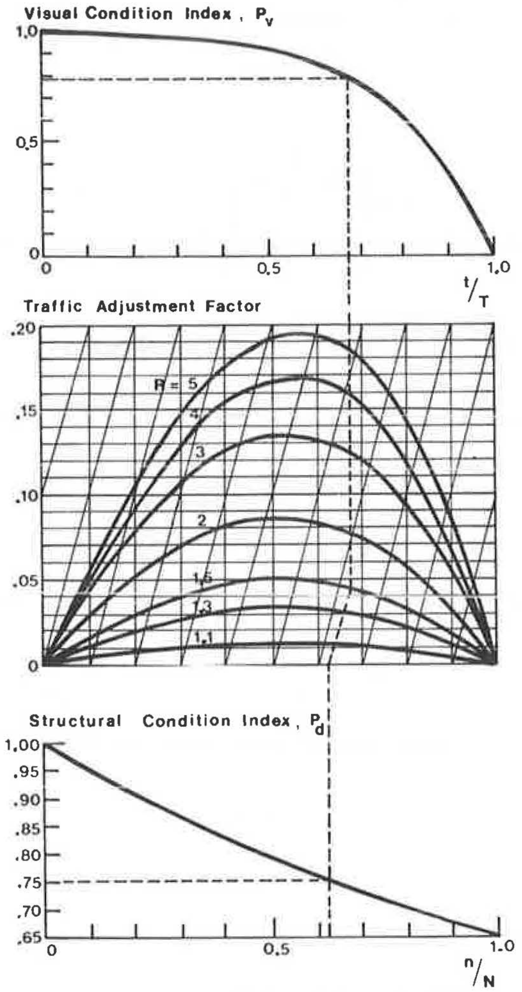


FIGURE 13 Relationship among structural condition index, allowable number of axle loads, and $S_{\log N}$ value.

For an accurate determination of the structural condition index, the equivalent layer thickness should be measured just after completion of the construction. Unfortunately, most deflection tests are only conducted on roadway sections with a poor condition. In those situations it is recommended to conduct deflection tests on locations not subjected to traffic loading to obtain candidate he_o values. In the Zuid-Holland test program, the area between the wheelpaths was used to estimate he_o. The he_n value was obtained from deflections measured in the wheelpaths.

In some cases, however, a structural condition index larger than 1 was obtained. This behavior is probably caused by extension of cracking from the wheelpaths to the area between the wheelpaths. Other reasons may be postcompaction of the granular base caused by traffic loads, which will cause a stiffening of the base in the wheelpaths, or differences in asphalt thickness in and between the wheelpaths caused by maintenance activities. In those cases the structural condition index can be assessed from the visual condition index (see Figure 14). The surface curvature index measured sets the minimum structural condition index. From the visual condition surveys, a life index t/T, which is based on years, is determined. This index can be converted to an index based on traffic intensities or axle load repetitions when the ratio of traffic intensity in year t=T over traffic intensity in year t=0 is known. The parameter $S_{\log N}$, as determined by deflection testings, determines the exact shape of the structural performance curve. But to avoid these conversions and to determine a proper value for the structural condition index, deflection measurements should be taken just before a new pavement construction opens to traffic.



Note: R = ratio of traffic intensity in year t = T over traffic intensity in year t = 0.

FIGURE 14 Conversion from visual condition index into structural condition index.

Overlays

In the Zuid-Holland Test program only overlays were taken into account as maintenance activities. The main objective for applying this type of maintenance was to reduce stresses and strains in the existing pavement structure and to reduce crack propagation through both the existing pavement structure and the overlay. The reduction required is a function of the structural condition required at the end of the design period, the amount of traffic to be carried, and the probability that the overlay design will be successful.

The overlay design method used in the Zuid-Holland test program has been outlined elsewhere (13,15). Here the most important aspects are summarized. The number of axle load applications (N_i) that the pavement can sustain for a probability of survival (P_i) is calculated from

$$\log N_i = a_o + a_1 b_o + a_1 b_1 \log he_i - u_i S_{\log N} \tag{5}$$

where

he_i = equivalent layer thickness,
u_i = standardized normal deviate associated with a probability P_i,
$S_{\log N}$ = standard deviation of the logarithm of the number of load repetitions to failure,
a_o, a_1 = constants from the relation $\log N = a_o + a_1 \log \varepsilon$, and
b_o, b_1 = constants from the relation $\log \varepsilon = b_o + b_1 \log he$.

If pavement life has to be extended, the required equivalent layer thickness can be calculated by using Equation 5. If N_1 is the number of allowable load applications for an equivalent layer thickness (he_1) and a probability (P_1), and if N_2 is the sum of the number of axle loads to be carried in the design period and for N_1, than for a probability of survival (P_2) the required equivalent layer thickness (he_2) can be calculated as follows:

$$\log (N_1/N_2) = a_1 b_1 \log (he_1/he_2) - u_1 S_{\log N} + u_2 S_{\log N} \tag{6}$$

if

$$J_i = 10^{u_i S_{\log N}} \tag{7}$$

Then Equation 6 can be rewritten into

$$he_2 = he_1 \sqrt[a_1 b_1]{N_2 J_2 / N_1 J_1} \tag{8}$$

The overlay thickness can be calculated by using Odemark's (14) theory:

$$h_o = (he_2 - he_1)/0.9 \sqrt[3]{E_o/E_s} \tag{9}$$

where

h_o = overlay thickness (m),
E_o = overlay stiffness (MPa), and
E_s = subgrade modulus (MPa).

Note that only information on the amount of traffic is needed in terms of a ratio for past traffic (see ratio N_2/N_1 is Equation 8). Exact knowledge of the axle load spectrum is not strictly necessary. Furthermore, note that an exact asphalt fatigue relation does not need to be entered, but that it can be confined to data on the slope of this relation.

The chosen overlay design life was for a 10-year period. Valk (16) indicated that an overlay design period of 10 to 15 years will result in the lowest costs. The structural condition index required at the end of the design period was set at 0.85, which involves only a slightly cracked pavement. The probability of survival required was set at 85 percent. The data in Table 4 give the overlay thicknesses, calculated in this way, for all the selected sections. Also given are data on what overlay thickness would be necessary if the determination was only based on construction data and visual condition surveys. Although for some sections the difference in overlay thickness can be up to 40 mm, the average thickness required equals that determined by using structural condition data. This proves that, on the network level, maintenance volume and costs can be estimated by visual condition surveys, but that for an accurate allocation of the budget to individual projects, structural condition data, as determined by deflection measurements, are necessary.

TABLE 4 Overlay Thickness for 10-Year Design Period

	Overlay Thickness (mm)		
Roadway Section[a]	Based on Deflection Measurements	Based on Visual Condition Surveys	Difference in Overlay Thickness (mm)
S 7 - L 4.6 - 5.0	87	79	−8
S 7 - R 4.6 - 5.0	86	79	−7
S 7 - L 6.3 - 6.9	71	81	+10
S 7 - R 6.3 - 6.9	73	81	+8
S 7 - L 11.8 - 12.3	31	52	+21
S 7 - R 11.8 - 12.3	81	52	−29
S15 - L 1.6 - 2.0	31	48	+17
S15 - R 1.6 - 2.0	20	41	+21
S15 - L 4.4 - 5.4	82	64	−18
S15 - L 5.4 - 6.0	67	64	−3
S15 - R 4.4 - 6.0	71	64	−7
S22 - L 0.9 - 2.0	39	79	+40
S22 - R 0.9 - 2.0	60	79	+19
S22 - L 3.4 - 5.1	71	83	+12
S22 - R 3.4 - 3.8	47	83	+36
S22 - L 23.3 - 23.4	66	43	−23
S22A - R 3.1 - 3.5	24	21	−3
S29 - L 9.0 - 10.0	25	19	−6
S29 - R 9.0 - 10.0	19	19	0
S30 - L 6.2 - 7.2	70	51	−19
S30 - R 6.2 - 7.2	68	51	−17
S36 - L 16.8 - 18.0	11	23	+12
S36 - R 16.8 - 18.0	16	23	+7
S40 - L 3.9 - 4.8	16	35	+19
S40 - R 3.9 - 4.8	23	35	+12
S47 - L 30.9 - 31.9	68	53	−17
S47 - R 30.9 - 31.9	68	53	−17
Avg	52	54	+2

Note: Data are for the Zuid-Holland secondary road network, 1982.

[a] Roadway sections selected by visual condition surveys.

CONCLUSIONS AND RECOMMENDATIONS

The results of tests of the DUPMS to a provincial roadway network have been presented. Some of the key issues involved in the test program are summarized as follows.

1. For a reliable assessment of pavement lives and a well-funded determination of maintenance or rehabilitation, an efficient structured accessible data bank is a prerequisite.
2. For the selection of maintenance projects, general visual condition surveys are recommended. Periodic surveys provide information on the performance of the visual condition.
3. A good assessment of the condition of roadway sections can be obtained by detailed visual surveys. To acquire uniform and consistent data, attention should be paid to the training of the inspectors.

Using sheets where the exact location of cracking can be drawn has proved to be valuable.

4. Visual condition surveys can be used for planning maintenance activities and estimating maintenance costs.

5. In the determination of the structural condition index, deflection tests should taken just after finishing the construction or application of a major maintenance strategy.

6. If the data mentioned in item 5 are not available, a comparative structural condition index can be obtained by conducting deflection tests both in and between the wheelpaths.

7. In roadway sections with a large extent of cracking, visual condition surveys have proved to be useful in the interpretation of the deflection basin.

8. Determining the overlay thickness (on the project level) by using only visual condition survey data and construction data is not recommended. On the network level, however, a reliable estimate of the average required overlay thickness can be determined in this way. On the project level, deflection tests should be used for an accurate determination of the structural pavement condition and the overlay thickness.

REFERENCES

1. A.A.A. Molenaar and C.A.P.M. van Gurp. A Pavement Management System for Provincial Roads in the Netherlands. Proc., 5th International Conference on Structural Design of Asphalt Pavements, Delft, Netherlands, 1982.
2. H. Valk, F.J.M. van Velzen, A.A.A. Molenaar, and C.A.P.M. van Gurp. The Delft University Pavement Management System Tested in Practice--Volume 1: Network Level. Report 7-82-115-33. Laboratory for Road and Railroad Research, Department of Civil Engineering, Delft University of Technology, Delft, Netherlands, 1982 (in Dutch).
3. H. Valk, F.J.M. van Velzen, A.A.A. Molenaar, and C.A.P.M. van Gurp. The Delft University Pavement Management System Tested in Practice--Volume 2: Project Level. Report 7-82-115-34. Laboratory for Road and Railroad Research, Department of Civil Engineering, Delft University of Technology, Delft, Netherlands, 1983 (in Dutch).
4. A.A.A. Molenaar and G.T.H. Sweere. Road Roughness: Its Evaluation and Effect on Riding Comfort and Pavement Life. <u>In</u> Transportation Research Record 836, TRB, National Research Council, Washington, D.C., 1981, pp. 41-49.
5. Pavement Management (Test Case Rhenen). Publ. 46. Study Centre for Road Construction, Arnhem, Netherlands, 1979 (in Dutch).
6. Manual and Distress Catalogue for the Visual Inspection of Roads. Study Centre for Road Construction, Arnhem, Netherlands, 1982 (in Dutch).
7. J.A. Epps, A.H. Meyers, I.E. Larrimore, and H.L. Jones. Roadway Maintenance Evaluation--User's Manual. Research Report 151-5. Texas Transportation Institute, Texas A&M University, College Station, 1974.
8. H.W. Kros, H. Valk, F.J.M. van Velzen, and A.A.A. Molenaar. Visual Condition Survey of Roads, System Description, Convergency and Consistency in Conduction by More Than One Survey Team. Report 7-82-115-28. Laboratory for Road and Railroad Research, Department of Civil Engineering, Delft University of Technology, Delft, Netherlands, 1982 (in Dutch).
9. A.A.A. Molenaar. Measurements on Frost Damage on Provincial Roads in Zuid-Holland. <u>In</u> The Winter of 1978-1979, Publ. N, Study Centre for Road Construction, Arnhem, Netherlands, 1980 (in Dutch).
10. C.A.P.M. van Gurp. Road Rating Programs for Visual Condition Surveys and Ride Index Measurements. Report 7-82-115-31. Laboratory for Road and Railroad Research, Department of Civil Engineering, Delft University of Technology, Delft, Netherlands, 1982.
11. A.A.A. Molenaar. Visual Condition Surveys: A Tool in the Planning of Maintenance of Road Pavements. WEGEN, Journal on Roads and Traffic, Vol. 55, No. 7, 1981 (in Dutch).
12. C.A.P.M. van Gurp. Pavement Life Assessment by Visual Inspections--Volume 1: Performance Models and User's Guide. Report 7-82-115-29. Laboratory for Road and Railroad Research, Department of Civil Engineering, Delft University of Technology, Delft, Netherlands, 1982.
13. A.A.A. Molenaar. Structural Performance and Design of Flexible Road Constructions and Asphalt Concrete Overlays. Dissertation. Laboratory for Road and Railroad Research, Department of Civil Engineering, Delft University of Technology, Delft, Netherlands, 1983.
14. N. Odemark. Investigations on the Elastic Properties of Soils and the Design of Pavements According to the Theory of Elasticity. State Road Laboratory, Stockholm, Sweden, 1949.
15. A.A.A. Molenaar and C.A.P.M. van Gurp. Structural Performance Model and Overlay Design Method for Asphalt Concrete Pavements. <u>In</u> Transportation Research Record 888, TRB, National Research Council, Washington, D.C., 1982, pp. 31-37.
16. H. Valk. Economic Evaluation of Structural Pavement Maintenance. Chair of Civil Economy, Department of Civil Engineering, Delft University of Technology, Delft, Netherlands, 1983 (in Dutch).

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